Dynamic Modelling, Validation and Analysis of Coal-fired Subcritical Power Plant

Eni Oko and Meihong Wang*
Process and Energy Systems Engineering Group, School of Engineering, University of Hull HU6 7RX.
*Corresponding Author: Tel: +44 1482 466688, E-mail: Meihong.Wang@hull.ac.uk

Abstract

Coal-fired power plants are the main source of global electricity. As environmental regulations tighten, there is need to improve the design, operation and control of existing or new built coal-fired power plants. Modelling and simulation is identified as an economic, safe and reliable approach to reach the objective. In this study, a detailed dynamic model of a 500 MWe coal-fired subcritical power plant was developed using gPROMS based on first principles. Model validations were performed against actual plant measurements and the relative error was less than 5%. The model is able to predict plant performance reasonably from 70% load level to full load. Our analysis showed that implementing load changes through ramping introduces less process disturbances than step change. The model can be useful for providing operator training and for process troubleshooting among others.

Keywords: Coal-fired power plants, dynamic modelling, model validation, process analysis, drum boiler, subcritical power plants

1. Introduction

1.1 Background

In 2011, coal-fired power generation contributed about 41% to world electricity generation (Siemens, 2012). This makes coal the largest single source of electricity. Future projections suggest that coal will remain a significant component of global energy mix regardless of increasing stringent environmental regulations. There is need however for more efficient design and operation of the power plant. This can be achieved by bringing in more process knowledge in the design, operation and control of the plant. Modelling and simulation is an economic, reliable and convenient approach for gaining more process knowledge and insight. The approach has been widely used for investigating the process behaviour of coal-fired subcritical power plants in literature (Kwan and Anderson, 1970; Cori and Maffezzoni, 1984; De Mello *et al.,* 1991; Lu, 1999; Lu and Hogg, 2000; Liu *et al.,* 2004; Li *et al.,* 2005; Colonna and VanPutten, 2007; Oke, 2008; Jinxing and Jiong, 2011; Lin and Yiping, 2011).

1.2 Process Description

In a coal-fired power plant, heat energy from coal combustion is used to generate steam. The steam enters a steam turbine at high pressure and consequently generates torque which is converted to electricity in the generator (Figure 1). Low pressure steam leaving the turbine is condensed and pumped back to the boiler. The entirely process basically follows a Rankine thermodynamic cycle though in reality there are other processes such as air pre-heating using combustion gases, feedwater heating using steam extracted from the turbine stages, and reheating steam between the turbine stages.

1.3 Motivations

As noted in the previous section, modelling and simulation of coal-fired power plant is necessary for studying the process behaviour. This can become useful for more efficient and reliable operation of the plant. Models of coal-fired power plants are widely reported in literature (Kwan and Anderson, 1970; Cori and Maffezzoni, 1984; De Mello *et al.,* 1991; Lu, 1999; Lu and Hogg, 2000; Liu *et al.,* 2004; Li *et al.,* 2005; Colonna and VanPutten, 2007; Oke, 2008; Jinxing and Jiong, 2011; Lin and Yiping, 2011).

However, most of these models consider only the boiler and turbines (Kwan and Anderson, 1970; Cori and Maffezzoni, 1984; Lu, 1999; Lin and Yiping, 2011). Without considering the feedwater heating sections, actual dynamic behaviour of the plant may not be captured accurately. This is because the power cycle is effectively treated as open loops (instead of a closed loop) without the feedwater heating trains. In Liu *et al.* (2004), and Lu and Hogg (2000) etc where the feedwater train was considered, no form of validation was provided. As such, there is little basis to establish the prediction accuracy of the models. Colonna and VanPutten (2007) presented a validated model with the boiler, turbine and feedwater system components. However, the authors assumed that the riser was electrically heated. This leaves out the furnace which is a key component.

In other studies, Oke (2008), Sanpasertparnich *et al.* (2010), and Lawal *et al.* (2012), development of models of subcritical coal-fired power plants was also reported. Again, the model reported by Sanpasertparnich *et al.* (2010) is a steady state model whereas that of Lawal *et al.* (2012) and Oke (2008) does not include some key dynamic characteristics such as the drum level. Jinxing and Jiong (2011) used fuzzy-based approach for modelling a dynamic model of a subcritical coal-fired power plant. Methods such as this are greatly hindered by the quality of data used. Also, it is difficult to generalize the ability of the model beyond the bound of data used in developing the model. With the aforementioned in mind, there is need for a dynamic model of a coal-fired power plant based on first principle which improves on the various areas of weaknesses identified in existing models.

1.4 Aim of the Paper and Its Novelty

The paper presents a dynamic model of a subcritical coal-fired power plant that captures the key dynamic behaviours over a wide operating range (70-100% load). Subcritical coal-fired power plants (steam pressure <221.2 bar) has been selected for the study because majority of existing coal-fired power plants are subcritical coal-fired power plant (Finkenrath *et al.*, 2012). Data for model validation are therefore more likely to be available.

As mentioned in the previous section, most dynamic models of coal-fired subcritical power plant reported in literature considered only the boiler and turbines. In contrast, complete model of the power plant with all the components (furnace, boiler, steam turbines, and condenser/feedwater heating train) is presented in this paper. Also, in contrast to Liu *et al.* (2004) where most of the components are modelled, steady state model validations at different load levels have been performed in this study. The model showed good predictions over wide operating conditions.

Also in this study, more details have been considered in describing the steam drum dynamics. This included the nonminimum-phase behaviour (i.e. the shrink and swell effect) of drum level dynamics (Åström and Bell 2000). This consideration sets the model presented here apart from the model presented in Oke (2008) and Lawal *et al.* (2012).

Process analyses were performed using the model presented. Our findings show that implementing load changes through ramping introduces less process disturbances than step change. Ramp change induces less process disturbance but requires longer time to achieve changes in load when compared to step changes.

2. Development of the Dynamic Model

Dynamic model of a 500MWe coal-fired subcritical power plant was developed based on general laws of heat, mass and momentum conservations (i.e. first principles).

2.1 Description of Reference Plant

The reference subcritical coal-fired power plant is a unit (500 MWe) of the now closed 2000 MWe Didcot A power station owned by RWE npower (Oke, 2008). The plant uses drum-type boiler with a three-stage tandem-compound, single-reheat steam turbine configuration. Also, it has a four-stage low pressure feedwater heater, three-stage high pressure feedwater heater and a deaeration unit. At 100% load, the main plant variables are shown in Table 1.

2.2 General Modelling Assumptions

Throughout the modelling exercise, we have kept in mind the need to maintain balance between fidelity and simplicity. This is made possible by a number of assumptions. Literature evidences show that these assumptions are reasonable (Oke, 2008). Assumptions specific to individual components are stated under the sections where the components are discussed. General assumptions adopted are as follows.

- Lumped parameter approach for modelling the various components.
- The various model constants have been derived from plant construction data (Oke, 2008).
- Energy losses and leakages of steam/water have not been taken into account.
- Bituminous coal was selected as the feed fuel (Table 2). The composition and its properties are assumed constant.
- The four-stage LP feedwater heaters and the three-stage HP feedwater heaters were lumped into single stage models respectively.

2.3 Modelling Equations

2.3.1 Furnace

Furnace model was chosen to be a zero dimensional model (Maffezzoni, 1992). This is due to the unavailability of data regarding temperature profiles within the furnace and the need for obtaining a simple model. Only radiant heat transfer component was considered, the convective heat transfer component is negligible (Blokh 1988, Yun-tao, *et al.,* 2008). Flue gas composition was obtained on the basis of 20 vol% excess air (at 100% load) and stoichiometric reactions involving carbon, hydrogen and sulphur. Other components of coal such as nitrogen and moisture etc are assumed inert.

Dynamics in furnace temperature was captured using energy balance equation (Equation 1). Mass balance was assumed to be steady state since gas flow adjusts quickly to changes in inlet conditions (Lawal *et al.*, 2012).

$$\dot{m}_{coal}(NCV_{coal} + h_{coal}) + \dot{m}_{air}h_{air} - \dot{m}_{gas}h_{gas} - \dot{m}_{ash}h_{ash} - Q_R = V_F\rho_g \frac{dh_g}{dt} \qquad (1)$$

The total radiant heat energy (Q_R) is estimated as follows :

$$Q_R = k\sigma V_F {T_g}^4 \cdot \frac{1}{\rho_g} \qquad (2)$$

The effective gas temperature is obtained using Equation (3):

$$T_g = \beta T_{g,ad} + (1-\beta)T_{FEGT} \qquad (3)$$

2.3.2 The evaporative loop

The evaporative loop includes the drum, downcomer, waterwall and riser tubes (Figure 2). Dynamic modelling of the loop reported by Lawal *et al.* (2012) was used here. In addition, we have accounted for *shrink and swell* characteristics (nonminimum-phase behaviour of drum level dynamics) in modelling the drum dynamics (Åström and Bell, 2000). *Shrink and swell* characteristics respectively refers to the fall or rise in drum level when the drum pressure changes. This behaviour is attributed to the existence of steam bubbles below the drum level. When drum pressure decreases, as it is the case when the steam valve is opened (during an increase in load), the bubbles tend to swell leading to rise in drum level and vice versa. To model drum level accurately will therefore require describing the distribution of steam bubbles below the drum level. This will at best be obtained using partial differential equations.

However, Åström and Bell (2000) outlined an approach for achieving this without partial differential equations. This approach was used here (details can be sought from Åström and Bell, 2000). The drum level is expressed more conveniently in terms of deviation from design point due to the complicated geometry of the drum.

$$l = \frac{V_{wD}+V_{sD}}{A_D} \tag{4}$$

A_D is measured at design condition.

2.3.3 Heat Exchangers

Dynamic equations on both steam and gas side have been used to model convective heat transfer in the superheater and reheater. Dynamic equations were only used on the water side in the feedwater heaters. The platen and secondary superheaters also accounted for radiative heat transfer. This is estimated based on Stefan-Boltzmann Law (Equation 2). The general equations for both side is expressed as follows:

Mass balance: $$\dot{m}_{in} - \dot{m}_{out} = V\frac{d\rho}{dt} \tag{5}$$

Energy balance: $$\dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + Q = \rho V\frac{dh_{out}}{dt} \tag{6}$$

Steam (or water) side: $$Q = U_s(\frac{1}{2}(\dot{m}_{in} + \dot{m}_{out})^{0.6})\left(T_w - T_{s,avg}\right) \tag{7}$$

Gas (or bleed steam) side: $$Q = U_g(\frac{1}{2}(\dot{m}_{in} + \dot{m}_{out})^{0.8})\left(T_{g,avg} - T_w\right) \tag{8}$$

2.3.4 Steam Turbines

The steam turbine model was obtained using the volume form of the established Stodola ellipse shown in Equation (9) (Lo *et al.,* 1990). The volume form is reported to be valid for all cases of compressible fluid compared to the temperature form which is only valid when the perfect gas law ($Pv = RT$) is assumed (Lo *et al.,* 1990). We have assumed constant turbine shaft speed and negligible leakage flows. Considering the rapid response capability of the steam turbine compared to the boiler, steady state models were used for the steam turbine.

$$\dot{m}_{in} = \frac{K_{SE}}{\sqrt{v_{in}}}\sqrt{\frac{{P_{in}}^2 - {P_{out}}^2}{P_{in}}} \tag{9}$$

$$\frac{T_{out}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} \tag{10}$$

2.3.5 Condenser

In the condenser, we only considered latent heat exchange between the cooling water and the condensing steam. Possible sub-cooling in the condenser was therefore ignored. Steady state conditions were assumed on the steam side. Dynamic equation similar to Equation (6) was applied to the cooling water side.

The condenser sump (hotwell) was considered separately. It was modelled as a holding tank as follows.

Mass balance:
$$\rho A \frac{dL}{dt} = \dot{m}_{in} - \dot{m}_{out} \tag{11}$$

Energy Balance:
$$\rho AL \frac{dh_{out}}{dt} = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} \tag{12}$$

2.3.6 Deaerator

The deaerator serves the basic task of removing dissolved gases from the boiler feedwater. It comprises of two parts, namely deaeration head and water collection tank. In this study, the chemical reactions involved in the deaeration process have not been considered. As a result, the deaerator model is represented as a simple holding tank involving steam and water mixing. This was modelled using equations similar to Equations (11) and (12).

2.3.7 Pumps

The boiler feed pump was modelled to be turbine-driven. The turbine is operated using steam extracted from the intermediate pressure (IP) turbine outlet. This was modelled as follows.

$$0.1047 K_{fptrb} \frac{dN_{bfp}}{dt} = Torq_{trb} - Torq_{bfp} \tag{13}$$

$$P_{bfp} - (P_{Dtorout} + g\rho Z) = K_0 \rho (0.1047 N_{bfp})^2 + K_1 \dot{m}_{bfp} \left(0.1047 N_{bfp}\right) + \frac{K_2 \dot{m}_{bfp}{}^2}{\rho} \tag{14}$$

The constants are derived from the pump characteristic equation. Additional details can be obtained from Masada (1979).

2.3.8 Governor Valve

The turbine governing method is assumed to be throttle governing which involves only one governor valve. The valve regulates steam flow to the turbine and consequently the turbine load changes. The key equation in the governor valve model is as follows:

$$m_{in}^{2} = K_{vf}^{2} v_{in} (P_{in} - P_{out}) \tag{15}$$

2.3.9 Control Loops

Main steam temperature (superheater outlet steam) is controlled using spray water attemperators. This involves mixing the steam with controlled flow of spray water to achieve desired temperature. Reheater temperature is controlled using rear gas pass biasing dampers which control the flow of flue gas along the divided rear pass. The fuel burn rate and governor valve both control power plant power output. The target power plant output is directly controlled by the governor valve; this target also sets the target drum pressure. The drum pressure is controlled by the fuel burn rate.

2.4 Whole Plant Model

The component models described above were implemented in modelling and simulation platform gPROMS and thereafter linked to obtain the whole plant model (See Figure 3). Physical properties of steam/water, air and flue gas have been determined through external property calls from Multiflash® based on Peng-Robinson property package. Specific enthalpies of coal and coal ash were obtained using specific heat capacity correlations by Lee (1967) and Richardson (1993) respectively (Equations (16) and (17)).

$$C_{p,coal}(Btu/lb\ \text{°F}) = 0.03464 + 2.261 \times 10^{-5} \cdot \mathrm{T} \tag{16}$$

$$C_{p,ash} = 191.2 + 2.238T - 1.464 \times 10^{-3} T^{2} \tag{17}$$

Derivatives of thermodynamic properties ($\frac{\partial \rho_s}{\partial P}, \frac{\partial \rho_w}{\partial P}, \frac{\partial h_s}{\partial P}, \frac{\partial h_w}{\partial P}, \frac{\partial T_s}{\partial P}$) used in the evaporative loop model were obtained using the NIST reference fluid properties (REFPROP) – DLL version 9.1.

3. Steady state model validation

3.1 Justification of steady state validation

Model validation is important for establishing some basis for the prediction capability of the model. For a model to be considered fit-for-purpose, it should be able to reasonably predict steady state values of different variables at different operating levels (or load). In addition, it should be able to demonstrate capability for predicting plant behaviour over time especially during periods when changes in load are implemented.

In this study, only steady state validation is performed. Dynamic validation was not performed due to lack of dynamic data in open literature for a coal-fired subcritical power plant. Also, gas side measurements for the reference plant are unavailable. As a result, the validations are limited to the steam side where measurements were obtained.

3.2 Inputs to the model

The inputs to the model include fuel burn rate, the governor valve stem position, cooling water flowrate, percentage excess air in furnace, attemperator water flow, condenser pressure, feedwater valve setting, and back pass damper setting.

3.3 Results

During the validation exercise, the model was first simulated at full load with the governor valve fully opened and the fuel burn rate at 52.2 kg/s. Key variables were then compared with plant measurements taken at a similar condition (Table 3). The results show that relative error in model predictions is within <5%. Considering the inherent errors in plant measurements, the model predictions can therefore be considered to be within acceptable range.

In addition, we have also performed comparison of different process variables at different load levels with plant measurements taken at similar load level. This comparison is necessary to determine the model capability away from full load condition. The model parameters remained unchanged for the different load levels tested. Main steam temperature and pressure were controlled and remained the same for the different load levels (568.69^{O}C and 170.92 bar respectively).

The model was simulated at 100%, 94.4%, 80% and 70% load levels corresponding to 500, 472, 400 and 350 MWe. The values of selected process variables at these conditions were compared against plant measurements at similar conditions (Figure 4 and 5). From the comparisons, the model predictions for the different load levels tested were within <5% relative error.

4. Process Analysis

4.1 Step Change in Load

Step changes in load were implemented to investigate the ability of the process variables to reach the next steady state condition. The total MWe is determined by the power plant power output controllers which manipulate the fuel burn rate and governor valve opening to meet the target power output. In this model, the controllers are PI controllers. During this exercise, the model was simulated at full load (500 MWe) for 200 seconds before it was stepped down to 470 MWe. The plant is maintained at this load level for a further 600 seconds.

As the load is stepped down from 500 to 470 MWe, the fuel burn rate also steps down correspondingly and steadies at a new value, 49.3 kg/s (Figure 6). The fuel burn rate initially drops below this level as the figure reveals before rising to the required level. In addition, drum pressure, drum level, circulation rate in evaporation loop, steam quality at riser outlet, feedwater mass flowrate at drum inlet, furnace pressure and economizer exit gas temperature have been assessed over the course of the change (Figure 6).

These variables show relatively fast response and reflect expected trends. For instance, as load decreased the drum pressure decreased. There was a rise in drum level reflecting the *swell* phenomenon in the drum. Feedwater mass flowrate initially rises and then dropped as expected before stabilizing. Furnace pressure showed a sharp drop before immediate recovering and stabilizing. This reflects decrease in air flowrate and it is expected for the circumstance. Economiser exit gas temperature dropped sharply and took about 5 mins (300 sec) to reach stable state.

4.2 Ramp Change in Load

Here, changes in load (total MW) are brought about by ramping. This is a typical procedure for implementing load change in an actual power plant. This load change approach has been assessed to compare it with step change approach. The total MWe is similarly determined by the power plant power output controllers which manipulate the fuel burn rate and governor valve opening to meet the target power output. The same controllers with the same settings used in section 4.1 are used here.

During the exercise, the model was maintained at 500 MWe (full load) for 100 seconds. The total MWe is then ramped down to 468.6 MWe over an interval of 700 seconds. It is then maintained at this load level for a further 500 seconds. Response of the fuel burn rate, drum pressure, drum level, circulation rate in evaporation loop, steam quality at riser outlet and feedwater mass flowrate at drum inlet have been assessed over the course of the change (Figure 7). The results are agreeable with expected trends in these variables whenever a load change is implemented in real life operation.

In comparison with step changes, ramping is implemented over a time range. The results show that ramp changes induce less fluctuation in the process variables on the steam side than step change during the course of the change. In reality, the strategy for implementing load changes is via ramping and our findings justifies the strategy.

5. Conclusions and Recommendation for future work

In this paper, dynamic modelling of a 500MWe subcritical coal-fired power plant was presented. The model was implemented and simulated using modelling and simulation tool gPROMS. Validation of the model predictions against plant measurements was also presented. Validation results show that the model is able to predict steady state conditions for as low as 70% load level within <5% relative error. Process analyses show that ramp change should be used for implementing load changes rather than step changes since the accompanying fluctuations in other variables are minimal.

Distributed model for the heat exchangers and the furnace can potentially improve model prediction accuracy. Consequently, it is recommended that distributed modelling approach be adopted for the heat exchangers and furnace in future modelling and simulation of coal-fired subcritical power plant.

Acknowledgement

The authors are grateful to the Natural Environment Research Council (NERC), Reference - NE/H013865/2, for financing this research. The financial support from EU FP7 (Reference: PIRSES-GA-2013-612230) is also acknowledged.

References

Åström, K. J. and Bell, R. D. 2000. Drum-boiler dynamics, Automatica*,* Vol. 36(3), pp. 363-378.

Blokh, A.G. 1988. Heat transfer in steam boiler furnaces. Hemisphere publishing corporation, London. ISBN 0-89116-626-2

Colonna, P. and VanPutten, H., 2007. Dynamic modelling of steam cycles. Part II-Simulation of a small simple Rankine cycle system. *Applied Thermal Engineering,* 27, pp. 2566-2582.

Cori, R. and Maffezzoni, C. 1984. Practical-optimal control of a drum boiler power plant. *Automatica*, Vol. 20, No. 2, pp. 163-173.

De Mello, F.P., Anderson, P., Doudna, J., Fish, J.H., Hamm, P.A.L., Hammons, T.J., Hurley, J.D., Kundur, P., Schulz, R., Tandy, G., Taylor, C.W and Younkins, K. 1991. Dynamic models for fossil fueled steam units in power system studies. *IEEE Transactions on Power Systems*, Vol. 6, No. 2.

Finkenrath, M., Smith, J., and Volk, D. 2012. CCS retrofit analysis of the globally installed coal-fired power plant fleet. Sustainable Energy Policy and Technology Directorate, International Energy Agency (IEA). Available at: http://www.iea.org/publications/freepublications/publication/CCS_Retrofit.pdf [Accessed Sept., 2013]

Jinxing, L. and Jiong, S. 2011. Non-linear modelling of drum-boiler-turbine unit using an evolving Takagi-Sugeno fuzzy model. *Int. J. Modelling, Identification and Control*, Vol. 12, Nos. 1/2.

Kwan, H.W., Anderson, J.H., 1970. A mathematical model of a 200MW boiler. *International Journal of Control*, 12(6), pp. 977-998.

Lawal, A., Wang, M., Stephenson, P. and Obi, O. 2012. Demonstrating full-scale post-combustion CO2 capture for coal-fired power plants through dynamic modelling and simulation. *Fuel,* Vol. 101, pp.115-128

Lee, A.L. 1967. Heat Capacity of Coal. Canadian Coal Conferences, March 30, Ottawa, Canada.

Li, B., Chen, T. and Yang, D., 2005. DBSSP–A computer program for simulation of controlled circulation boiler and natural circulation boiler start up behaviour. *Energy Conversion and Management,* 46(4), pp. 533-549.

Lin, G. and Yiping, D. 2011. A new linear model of fossil fired steam unit for power system dynamic analysis. *IEEE Transactions on power systems*, Vol. 26, No. 4.

Liu, C., Liu, J., Niu, Y., and Jin, X., 2004. Nonlinear modelling and simulation for large scale coal-fired power unit. In: *30th Annual Conference of the IEEE Industrial Electronics Society,* Busan, Korea, Nov. 2-6.

Lu, S. 1999. Dynamic modelling and simulation of power plant systems. *Proc Instn Mech Engrs, Part A, Journal of Power and Energy,* Vol. 213, pp. 7-22.

Lu, S. and Hogg, B.W. 2000. Dynamic nonlinear modelling of power plant by physical principles and neural networks. *Electrical Power and Energy Systems*, Vol, 22, pp. 67-78.

Maffezzoni, C. 1992. Issues in modelling and simulation of power plants. In Proceedings of IFAC symposium on control of power plants and power systems, Vol. 1, pp 19-27, Munchen, Germany.

Masada, G.Y. 1979. Modelling and Control of Power Plant Boiler-Turbine—Generator Systems, Sc. D Thesis, Department of Mechanical Engineering, MIT.

Oke, O. O., 2008. Dynamic modelling of subcritical coal-fired power plant. MSc Thesis, Cranfield University.

Richardson, M. J. 1993. The specific heats of coals, cokes and their ashes. *Fuel,* Vol. 72(7), pp. 1047-1053.

Sanpasertparnich, T., Idem, R., Bolea, I., DeMontigny, D., Tontiwachwuthikul, P., 2010. Integration of post-combustion capture and storage into a pulverized coal-fired power plant. *International Journal of Greenhouse Gas Control*, Vol. 4, pp. 499–510

Siemens, 2012. Siemens to focus its renewable energy activities on wind and hydro power. Available at: http://www.internationalsustainableenergy.com/6727/news/siemens-to-focus-its-renewable-energy-activities-on-wind-and-hydro-power/ [Accessed Jan., 2014]

Spirax-Sarco, 2014. Water-tube boilers. Available at: http://www.spiraxsarco.com/resources/steam-engineering-tutorials/the-boiler-house/water-tube-boilers.asp [Accessed March 2014]

Yun-tao, C., Chun, L., Qiang, C., Huai-chun, Z., 2008. Distributed parameter modelling and simulation for the evaporation system of a controlled circulation boiler based on 3-D combustion. *Applied Thermal Engineering*, Vol. 28, pp. 164-177.